Experiments in Electrodynamic Levitation and Toroidal Dipole Moment

Society of Physics Students

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Abstract:

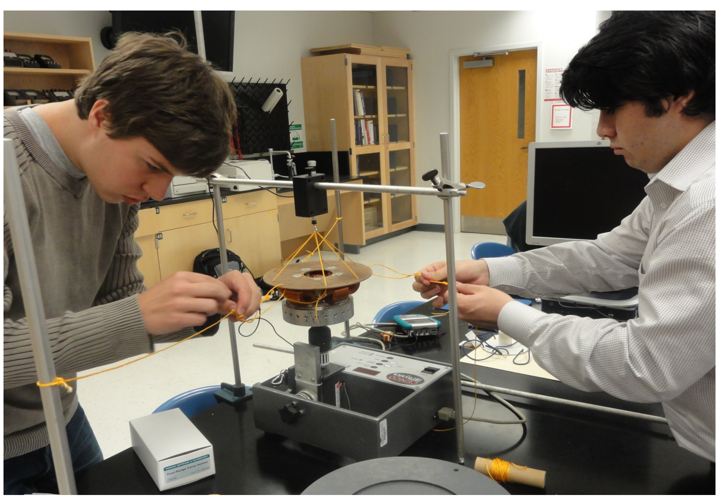
The purpose of this proposal is twofold. First is to complete a presentable laboratory model of inductive magnetic levitation of a rotating circular Halbach array supported and stabilized by a system of inductive coils, as an axial and radial electrodynamic bearings. Second is to explore properties of a physical model of a toroidal dipole moment.

Passive magnetic bearing systems are very advantageous in many technical applications, for example in flywheel energy storage systems (electromechanical batteries). We are going to experiment with different sets of rotating Halbach magnets and induction coils, investigating possible equilibrium configurations.

A toroidal coil with DC or AC current, or a toroidal magnet with azimuthal magnetization, at rest or rotating, both have very interesting physical properties, permitting to measure directly the time-dependent vector magnetic potential, frequently considered to be just a mathematical device.

Electrodynamic levitation

Here at Northern Virginia Community College's SPS branch, our team is actively continuing research into inductive magnetic levitation as a model for passive magnetic bearings. We are currently working on refining a project carried over from the previous semester that has produced reliable and repeatable data. By rotating a periodic circular Halbach array of Nd magnets under a system of five 4 mH short-circuited copper air core solenoid coils, having a resistance of 1.7 ohms each, we have achieved up to four newtons of lift of the coils system.



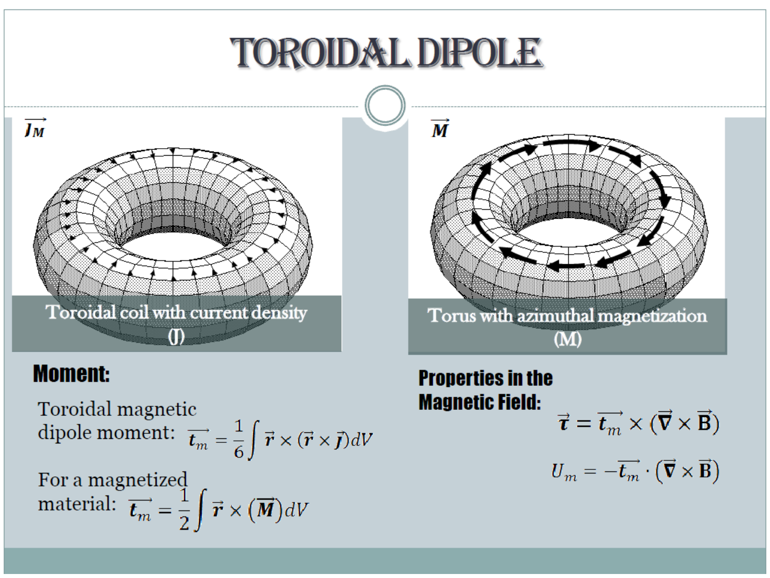
Austin and Ricardo experiment on rotating circular Halbach array - they measure a repulsive magnetic force on a coil system suspended on a force sensor.

Based on our collected data and the corresponding theoretical model, we propose several changes in the construction of a new coil array that will produce higher repulsive forces. We also want to add a dedicated motor/generator to rotate the magnet above the coil system and to add side coils to provide restoring forces for radial stabilization of the levitating magnet. We will also experiment with a system involving two Halbach rings magnetized in the opposite directions.

Beginning with the mathematical model describing inductive magnetic lift vs. drag forces acting from the coils as $\frac{F_L}{F_D} = \frac{2\pi v L}{\lambda R}$ where v is the tangential velocity of the magnet on the rim, L is the inductance of a coil, λ is the length of one period of the Halbach array, and R is the coil's resistance, we realize that two variables can be modified by changing the coil array, one being the inductance and the other resistance. In order to increase the inductive value of the new coil array, we may use of research made public by Lawrence Livermore National Laboratory in similar experiments. We've come to a conclusion after analyzing their equation relating the ratio of available levitating force to its limiting value $\frac{F_L}{F_{max}} = \frac{w}{P_c}(\frac{L_d}{L_L+L_d})$, where w is the width of the Halbach array, P_c is the perimeter of the coil, L_d is the inductance of the coils themselves , L_L is the extra inductance provided by inductive loading, and Fmax is the maximal levitating force. We may be able to increase induction through inductive loading by adding ferrite tiles or toroids to the new coil array. Through experimentation, we will determine whether inductive loading works effectively in a circular system with a constantly fluctuating magnetic field.

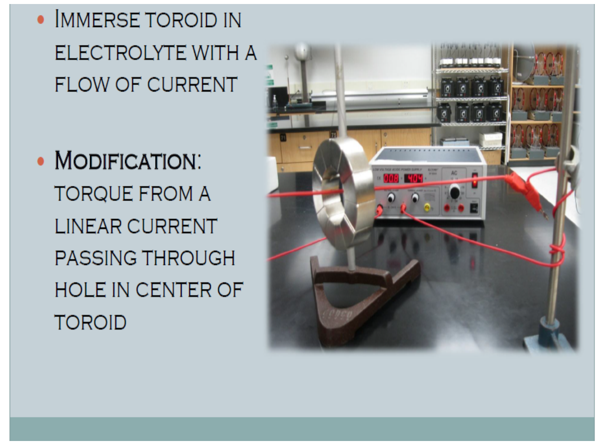
Adding capacitors: Building on our experience with magnetic induction, our team has decided to explore more advanced concepts in the field of magnetics. Due to the sinusoidal nature of the magnetic field in our experiment, there exists an electromagnetic frequency that varies with the tangential velocity of the Halbach array. In our system characterized by 12 magnets the relation between rotational velocity Ω and the angular frequency ω of the voltage pulses in coils is given by ω = 6 Ω. With the flux = $\varphi_0\sin(\omega t)$, voltage induced in coils' circuits is $V(t) = \omega\, \varphi_0\cos(\omega t)$ (Faraday's Law), and the R-L circuit equation is V(t) = L*di(t)/dt + R*i(t). After adding a series capacitor C, the equation becomes V(t) = L*di(t)/dt + R*i(t) + q(t)/C. This driven RLC circuit equation will be the starting point of our theoretical analysis.

In the experiments, we will measure angular velocity, induced currents and magnetic fields in the coils, the lift force and the drag torque. We will test how lift/drag ratio increases with the speed of rotation. Our goal will be to achieve a stable axial levitation of the Halbach magnet by one inductor system, with the magnet stabilized radially by a another coil system. We will be using different sensors of physical quantities available at our college laboratory, combined with two interface systems: Pasco DataStudio and Vernier LabQuest.

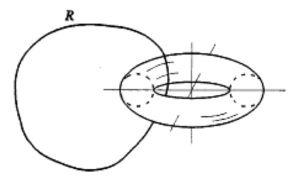


Experiments with toroids

A physical model of a static toroidal dipole moment is a small toroidal coil with DC current, or a toroidal magnet magnetized circumferentially. Their entire magnetic field is concentrated inside the torus, only magnetic vector potential **A** has non-zero values outside of it. Both toroids interact with curl **B**, that is, with an external conduction or displacement current. Our first series of experiments will consist in passing a wire with strong current inside the hole of the toroid, and measuring toroid's period of oscillations as a function of the applied current, to find the toroidal dipole moment, to be compared with a theoretical calculation. Another option is to immerse the toroid in the conducting fluid under voltage, to observe the torque produced by the current density term μ_0 **j** flowing in the fluid. Interaction with a displacement current $\varepsilon_0 \mu_0 d\mathbf{E}/dt$ could be observed by a torque exerted on the toroid by suddenly collapsing electric field between plates of a discharging capacitor.



Next we will experiment with toroidal antenna – by passing AC current with amplitude I through the coil toroid or rotating the magnetic torus along axis perpendicular to its principal axis. Time-dependent magnetic flux Φ from such an antenna will give rise to an electric dipole radiation, and in the near zone – to quasi-static variable electric and magnetic fields: dipole electric $E \approx \omega I/r^3 \sin\omega t$ and azimuthal $B \approx \omega^2 I/r^2 \cos\omega t$.



This variable electric field may be detected by using a test wire loop of resistance R encircling the electric toroid, after which it develops an EMF $\epsilon = \int_{wire} \mathbf{dl} \cdot \mathbf{E} = - d\Phi/dt$. A current sensor with the LabQuest, inserted into the loop, will detect a current ϵ /R, and we could record then also the total charge moved through the wire $Q = \int(\epsilon/R)dt = -(1/R)\int_{wire} \mathbf{dl}\cdot \mathbf{A}$, which will give us a direct measure of the vector potential **A**. Magnetic field of the toroidal antenna will be detected using a sensitive magnetometer connected to an interface LabQuest.

Timeline: We will be working in two groups, each using different passive bearings systems for levitation and sidewise stabilization, and the third group will be experimenting with the toroids, for the total of 15 chapter members. Due to our need for very specific and variable designs, many materials will be ordered raw and designs will be made in the machine shop at NOVA Annandale campus. Therefore, the spring semester will be used to construct the new coil arrays, new Halbachs and toroids and produce levitation. In the fall we will do a long series of measurements. This experiment can then be used as a demonstration to other colleges, local high-schools and scientific seminars. In the fall, we will also begin construction and testing of the newer aluminum designs and LRC design (adding capacitors to inductors).

- **Inductrack Demonstration Model**, Post, Richard F., Report UCRL-ID-129664, February 3, 1998.
- **Electrodynamic Passive Magnetic Bearings with Planar Halbach Arrays,** Jan Sandtner**,** Silphenix GmbH, CH-4436 Oberdorf, Sonnenweg 10, Switzerland, et al.
- **Development of a Passive Magnetic Bearing System for a Flywheel Energy Storage**, Chan Ham**,** Mechatronics Engineering, Southern Polytechnic State University, Marietta, Georgia 30060, USA, et al.
- **Ambient-Temperature Passive Magnetic Bearings: Theory and Design Equations,** R. F. Post, D. D. Ryutov UCRL-JC-129214 PREPRINT (1998).
- **On the Fields of a Torus and the Role of the Vector Potential**, N. J. Carron**,** American Journal of Physics, August 1995, Volume 63, Issue 8, pp. 717.
- **Experiments in Inductive Magnetic Interactions**, Robert Argus, Jonathan Mills, Tony Nguyen, Omar Moran, Zaeema Zafar, presented at Chesapeake Section of the American Association of Physics Teachers, Spring 2012 meeting, Arlington, VA, March 31, 2012; Innovative STEM Symposium, ISS Research Presentations**,** Morgan State University, Baltimore, MD, March 10, 2012.

Proposed Budget

12 Nd magnets from K-Magnetics for additional circular Halbach array: $432

12 Nd magnets from K-Magnetics for new magnetic toroid: $432

5 coils for axial levitation and radial stability, 10 mH, 15 AWG from Jantzen: $294

3 motors or motor/generators, from A.O. Smith or Kollmorgen: $450

Ferrites, capacitors: $200

Low-friction support for toroid experiments: $150

Total: $1,958

The rest of the lab equipment is provided by the College, hardware parts will be manufactured at the College's machine shop.